

Do LEP results suggest quarks have integer electric charges?

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Abstract: We argue that recent results from two-photon processes at LEP are better explained by quarks possessing integer electric charges.

Photon-photon collisions have been very thoroughly studied over the past years [1]. It has been established [2, 3] that the photon may interact both as a point-like particle, the so-called “direct” processes described by perturbative QED and QCD, and as a composite structure, through “resolved” processes. In the latter it is believed that one of the photons first fluctuates into an hadronic state and those partons interact with the second photon. Double resolved processes where both photons behave as having a structure are also possible. These processes clearly require non-perturbative physics and their theoretical description is thus quite complex. Two-photon physics has been successful in reproducing most results from particle accelerators up to LEP2 energies [4] though requiring Reggeon and Pomeron parameterizations [5] to fit, for instance, the total cross section of hadron production by two photons [6] - at LEP2 energies, in fact, this process is the main source of hadron production. However, recent LEP2 results on two-photon physics have raised a problem: both on open heavy quark and inclusive hadron production processes, next-to-leading-order (NLO) calculations in the Standard Model (SM) severely underestimate the data. The SM prediction for bottom quark pair production via the two photon channel is a factor of 3 lower than the observed result [7]; larger discrepancies are found for the differential cross section for the inclusive production of π^0 [8], π^\pm and K^\pm [9] at high values of the particles’ transverse momentum. A possible explanation for the discrepancy on the $b\bar{b}$ cross section was given in ref. [10], requiring a supersymmetric model with a light colour octet gluino, although the agreement found there is not satisfactory. A hypothesis put forth for the latter discrepancies is that of multijet events at high p_T not taken into account in the theoretical calculations [11]. In this letter we propose a different solution, that quarks have integer electric charges and the cross sections under study in two-photon processes at LEP2 energies come mostly from perturbative processes.

Integer charged quark (ICQ) theories were first proposed by Han and Nambu [12]. A renormalisable version was first obtained by Pati and Salam [13] and several ICQ theories have been obtained via gauge symmetry breaking, differing on the initial gauge group, generally larger than the SM’s. Witten remarked [3] that the reaction $e^\pm e^\pm \rightarrow e^\pm e^\pm q \bar{q}$, via the two-photon channel, is the preferential process to establish the character of the quarks’ electric charges. In fact, as we shall shortly see, the perturbative cross sections for this reaction are very different for an ICQ theory or a fractionally charged quark (FCQ) one, as opposed to all reactions involving a single photon: it is a well known fact that such processes cannot distinguish between ICQ and FCQ models. In this letter we will compare the FCQ and ICQ predictions for open charm and

bottom cross sections at LEP2 and show, in section 1, that where the SM fails an ICQ theory fits the data admirably well. In section 2 we will study inclusive hadron production at LEP2 and again we will show that ICQ theories fit the experimental results better than the SM. In section 3 we will review the experimental evidence for fractional quark charges and argue it is not conclusive.

1 Open heavy quark production in two-photon collisions at LEP2

As can be appreciated in figure (1), it is possible to reproduce the total cross section for the production of charm pairs at LEP2 by using contributions from both direct and resolved processes, at next-to-leading-order (NLO) in QCD. In the same plot we see that even with substantial contributions from resolved processes the theory is unable to reproduce the data for bottom quark production. The Standard Model prediction is a factor of 3 lower than the experimental results. It is clear from fig. (1) that perturbative physics alone is insufficient, in the SM, to reproduce the experimental results, this despite the theoretical predictions having some dependence on the input quark mass and the choice of renormalisation scale. Detailed measurements of the photon structure functions revealed the importance of their non-perturbative component - at low energies or transverse momentum it is impossible to disentangle the perturbative contributions from the non-perturbative ones. However, it seems a reasonable expectation that at the very high LEP2 energies the non-perturbative contributions should be small (that is certainly true for FCQ theories, see for instance ref. [14]). Plus, for charm or bottom quark production, the mass of these quarks being so large, we have a “natural” large scale for QCD processes. Once again, it seems reasonable to assume that perturbative physics should dominate. We will take this as our starting point and calculate only perturbative cross sections.

We will see in section 3 that single photon reactions give identical results for ICQ or FCQ theories. There we will give a general argument for why it is so but for the moment let us consider a particular example, that of the quantity $R = \sigma(e^+e^- \rightarrow q\bar{q})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$. We begin by noting that we do not observe quarks of a given colour individually, rather mesons or baryons containing them; as such the amplitude of the process $e^+e^- \rightarrow q\bar{q}$ is the sum of the amplitudes for each quark’s colour,

$$\mathcal{M}(e^+e^- \rightarrow q\bar{q}) = \sum_{i=1}^3 \mathcal{M}(e^+e^- \rightarrow q^i\bar{q}^i) \quad . \quad (1)$$

Now, the probability of “finding” a quark of a particular colour in the final state is 1/3, so the cross section $\sigma(e^+e^- \rightarrow q\bar{q})$ is proportional to the square of the modulus of the amplitude (1) multiplied by a factor of 1/3 and the quantity R is given by

$$R = \frac{1}{3} \sum_q \left(\sum_{i=\text{colours}} e_q^i \right)^2 \quad , \quad (2)$$

where e_q^i is the electric charge of quark q with colour i . It should be noted that in ICQ theories quarks have charges that depend on their colour index. An up-type quark, for instance, has charge $(+1, +1, 0)$ for the quark’s colour indices $(1, 2, 3)$. For a down-type quark, the charge is $(0, 0, -1)$. It is then trivial to see that for both ICQ and FCQ theories we obtain the same contributions to R (4/3 from an up-type quark, 1/3 from a down-type one). The existing measurements of R are not proof of FCQ - rather, they make a very good case for the existence of colour. Unlike R , the quantity $R_{\gamma\gamma} = \sigma(e^+e^- \rightarrow e^+e^-q\bar{q})/\sigma(e^+e^- \rightarrow e^+e^-\mu^+\mu^-)$ (both

processes going through the two-photon channel) gives very different results for both types of theory, namely (at tree-level):

$$\begin{aligned} R_{\gamma\gamma}^{FCQ} &= 3 \sum_q e_q^4 \\ R_{\gamma\gamma}^{ICQ} &= \frac{1}{3} \sum_q \left(\sum_{i=\text{colours}} e_q^{i^2} \right)^2. \end{aligned} \quad (3)$$

Notice how the ICQ result reduces to the FCQ one when the quark electric charges do not depend on the colour. From equation (3) we deduce immediately that for an up-type quark we would have $R_{\gamma\gamma}^{ICQ}/R_{\gamma\gamma}^{FCQ} = 9/4$ and for a down-type one, $R_{\gamma\gamma}^{ICQ}/R_{\gamma\gamma}^{FCQ} = 9$. Given that the production of muon pairs occurs identically in both models the cross section for the production of charm pairs by photon-photon collisions in an ICQ theory is 9/4 the value of the same quantity calculated in an FCQ model. For bottom production, the ICQ cross section is 9 times greater than the FCQ one. At this point we are ready to compare ICQ and FCQ predictions for open heavy quark production - we follow the procedure of ref. [14] to calculate $\sigma(e^+e^- \rightarrow e^+e^-q\bar{q})$ in the Equivalent Photon Approximation [15]. We use their suggested spectrum of Weizsäcker-Williams photons and cut-off on the photon's maximum virtuality. We set the free quark production thresholds at $(3.8 \text{ GeV})^2$ (for charm quarks) and $(10.6 \text{ GeV})^2$ (for bottom quarks). In figure (2) we show the tree-level cross sections. The dashed lines are the FCQ results (in agreement with the values of ref. [14], the solid lines the ICQ ones. The comparison with fig. (1) is revealing - the ICQ theory not only describes as well the production of charm pairs, it also succeeds where the SM fails, the production of bottom quarks.

The QCD corrections to this calculation should improve the agreement, as we expect them to increase the tree-level cross section (by no more than 30% for the SM). In ICQ theories gluons generally acquire mass and electric charge; the QCD corrections will depend on the particular model we choose. We give two examples: in ref. [16] a model was considered with eight massive gluons of mass $\sim 0.3 \text{ GeV}$ to explain the $\gamma\gamma$ results from PETRA. More recently massive gluons of mass about 1 GeV were considered to explain the radiative decays of the J/Ψ and Υ mesons [17]. For such reasonably low gluon masses we expect the NLO QCD corrections from the SM to be similar in form to those of the ICQ theory. A good estimate of the NLO QCD ICQ cross section is therefore to multiply the “direct” results of fig. (1) by factors of 9/4 and 9 for the charm and bottom quarks respectively. As can be seen from table 1 the agreement between data and these estimated ICQ predictions is, again, excellent. Recently [18] an ICQ model with three massless gluons and five massive ones, with masses larger than $\sim 76 \text{ GeV}$, was proposed. In such a model the gluon bremsstrahlung corrections will involve only three gluons, not eight. Also, given that the gluons' mass is so large, an approximation to the one-loop cross section would be to consider the contributions of the massless gluons alone. So, from the results of ref. [14], an estimate of the one-loop QCD correction to the FCQ cross section would be

$$\sigma(\gamma\gamma \rightarrow q\bar{q})_{1-loop} \simeq \frac{12\pi\alpha^2 e_Q^4}{s_{\gamma\gamma}} \beta \frac{3\alpha_s}{4\pi} \left[\frac{\pi^2}{2\beta} - \left(5 - \frac{\pi^2}{4} \right) + O(\beta) \right], \quad (4)$$

where $s_{\gamma\gamma}$ is the two-photon total energy squared and $\beta = (1 - 4m_q^2/s_{\gamma\gamma})^{1/2}$, with m_q the quark mass. With three massless gluons the $SU(2)$ Casimir 3/4 appears. Repeating the calculations that led to fig. (2) we see that this estimated correction increases the cross sections by no more than $\sim 7\%$. This is probably an underestimation of one-loops effects and it improves the agreement with the experimental results only slightly.

An exact calculation for particular ICQ models, including NLO QCD corrections, is clearly necessary at this stage. Such calculation could put bounds on the masses of the ICQ gluons (or

\sqrt{s} (GeV)	ICQ predictions	Exp. Data
91	563 - 722	460 ± 92.2
133	680 - 925	1360 ± 300
167	770 - 982	940 ± 172.1
183	817 - 1125	1290 ± 149.7
194	900 - 1181.3	1016 ± 123.7
194 ($b\bar{b}$)	14 - 16	13.1 ± 3.1

Table 1: Comparison of estimated ICQ NLO QCD predictions with experimental data [7]. The ICQ cross sections are obtained from the “direct” curves of fig. (1). All cross sections are in picobarn and, except for the last line, refer to the reaction $e^+e^- \rightarrow e^+e^- c\bar{c}$.

the colour-breaking vevs of ref. [18]). As striking as the numerical agreement is the fact that we obtained these results from a purely perturbative ICQ theory. More detailed calculations or measurements would indicate if there is the need of a (small, surely) non-perturbative component to the cross sections at these high energies. A small resolved component seems necessary to improve the charm cross section, judging by our estimated results. Let us also emphasize that the analysis that led to the experimental data presented in refs. [7] assumed normal QCD backgrounds. With all rigor that analysis would have to be re-made assuming a gluon (massive or otherwise) background from an ICQ theory, but it seems reasonable to expect the end results would not be significantly different from those now available.

2 Inclusive hadron production in two-photon collisions at LEP2

Unlike the total $c\bar{c}$, $b\bar{b}$ cross section, even a leading order (LO) calculation for an inclusive process requires some non-perturbative input in the form of fragmentation functions. In fact, in inclusive processes we are interested, not in the result of the partonic interaction (like in the open channels) but rather on a specific hadron appearing from the hadronisation of quarks. For the reaction $e^-(P_1) + e^+(P_2) \rightarrow h(P_h) + X$ via the two-photon channel the differential cross section for inclusive production of a given hadron h (with four-momentum P_h , rapidity y and transverse momentum p_T is given, at LO, by

$$\frac{\partial\sigma}{\partial y \partial p_T} = \frac{2p_T}{S} \sum_l \int_{1-V+VW}^1 \frac{dz}{z^2} \int_{VW/z}^{1-(1-V)/z} \frac{dv}{v(1-v)} f_-(x_1) f_+(x_2) D_l^h(z, M_F^2) \frac{d\sigma_{\gamma\gamma \rightarrow l\bar{l}}}{dv} \quad (5)$$

where S , V and W are the usual Mandelstam variables, defined by $S = (P_1 + P_2)^2$, $V = 1 + T/S$ and $W = -U/(S + T)$, with $T = (P_1 - P_h)^2$, $U = (P_2 - P_h)^2$. We also define the partonic Mandelstam variables s , t , u and v using the four-momenta of the partons instead of that of the external particles: if P_1^γ , P_2^γ and P_q are the momenta of the photon emitted by the electron and positron and the momentum of the hadronising quark we have $s = (P_1^\gamma + P_2^\gamma)^2$, $t = (P_1^\gamma - P_q)^2$, $u = (P_2^\gamma - P_q)^2$ and $v = 1 + t/s$. s is clearly the center-of-mass energy of the two-photon system. In equation (5) x_1 , x_2 and z are the momentum fractions carried by both photons and the hadron (thus defined as $P_1^\gamma = x_1 P_1$, $P_2^\gamma = x_2 P_2$ and $P_h = z P_q$), related to each other by $x_1 = VW/vz$ and $x_2 = (1 - V)/z(1 - v)$. $f_-(x_1)$ and $f_+(x_2)$ are the probability functions for finding a photon inside the electron or positron with momentum fractions x_1 and x_2 respectively. $D_l^h(z, M_F^2)$ is the fragmentation function of a quark of flavour l into a hadron h carrying a fraction z of l 's momentum. It is evaluated at an *a priori* unknown fragmentation scale M_F . Finally, the last term in this expression is given by [14, 19]

$$\frac{d\sigma_{\gamma\gamma\rightarrow l\bar{l}}}{dv} = \frac{2\pi\alpha^2 C_F}{s} \left[\frac{t}{u} + \frac{u}{t} + 4 \frac{s m^2}{t u} - 4 \left(\frac{s m^2}{t u} \right)^2 \right], \quad (6)$$

where m is the mass of the quark l (set to zero if $l = u, d, s$) and C_F is a colour factor, related to the fourth power of the quarks' electric charges. For an FCQ theory, C_F equals $16/27$ and $1/27$ for up and down type quarks respectively. For an ICQ theory, those factors become $4/3$ and $1/3$. The fragmentation functions D_h^l are not known from first principles: they must be extracted from experimental data and are inherently non-perturbative in nature (though their evolution with the scale M_F is governed by an Altarelli-Parisi type equation). For pions, for instance, NLO parameterizations were first given in [20]. The current state-of-the-art fragmentation functions, parameterized to include scale dependence in a very useful manner, were elaborated by Kniehl *et al* [21] and will be used throughout this paper (at LO only for consistency, since we use the tree-level partonic cross section in eq. (5)).

At this point let us consider the current experimental data from the L3 collaboration for inclusive π^0 photoproduction at LEP2 [8]. As is plain from fig. (3) there is a huge discrepancy between the NLO QCD SM prediction and the actual data for $p_T \geq 5$ GeV, a discrepancy that grows worse for higher values of p_T : for $p_T \simeq 17$ GeV the SM prediction is roughly 6 times smaller than the experimental data. This is not a new fact: Gordon [22] compared the first NLO QCD calculation for inclusive π^0 photoproduction with MARKII data [11] and concluded that a discrepancy between theory and experiment at high p_T was already present. The other important piece of information to retain from fig. (3) is that at low p_T , as expected, it is the non-perturbative resolved contributions that dominate, whereas at high p_T the direct processes constitute the bulk of the cross section. We will perform only a LO perturbative calculation so we cannot expect to find good agreement in the low p_T region - but an ICQ theory should increase the high p_T agreement considerably. Consider: in an ICQ theory the partonic cross section $\sigma_{\gamma\gamma\rightarrow q\bar{q}}$ in eq. (5) is multiplied by a factor of $9/4$ (*vis a vis* the FCQ cross section) for $q = u, c$ and a factor of 9 if $q = d, s, b$. However, unlike the open channel, we do not expect the ICQ cross section to be given simply by an overall multiplicative constant times the FCQ result - in fact, the charm quark contribution to eq. (5) does not “kick in” until s has values superior to the charm production threshold (set to 2.97 GeV in the fragmentation functions of ref. [21]). Likewise the bottom contribution only affects the cross section for s larger than the $b\bar{b}$ threshold, set to 9.46 GeV. Because $s = p_T^2/z^2 v(1 - v)$ the ICQ contributions are therefore larger, compared to the FCQ ones, for larger p_T : for instance, if above the charm threshold the FCQ charm contribution is, say, X , the ICQ term will be $9X/4$. Above the $b\bar{b}$ threshold the bottom contribution would be Y , so the FCQ cross section would be given by $X + Y$; the ICQ one would thus equal $9X/4 + 9Y$. So, the ICQ cross section is always larger than the FCQ one, and the ratio between the two is expected to grow with p_T . This behaviour is exactly what we

need to explain the discrepancy in fig. (3) - multiplying the direct FCQ cross section by a single numeric factor would be useless, but the ICQ prediction is that that factor increases with the value of p_T .

We follow closely the calculation of ref. [22], adopting their Weizsäcker-Williams [15] spectrum; the LO fragmentation functions of [21] are used with the fragmentation scale initially set to the standard value $M_F = p_T$. The tree-level cross section we present in figure (4) is in agreement with the results of [22, 8]. Multiplying the partonic cross sections by the appropriate factors gives us the ICQ cross section - it is clear there is a dramatic improvement over the FCQ prediction for high p_T . Obviously, at low p_T we do not agree (FCQ or ICQ) with the data. As explained that was to be expected, since in that region the resolved processes are dominant and we are not including them in this calculation. The horizontal error bars in this plot are calculated from the power law fits to the cross section performed by the L3 collaboration: for $p_T \geq 1.5$ GeV they found that the cross section goes like $\sim p_T^{-4.1}$ [8]. With this power law it is a trivial matter to calculate the root mean square deviation for the p_T bin intervals considered in the experiments. For instance, for the 15-20 GeV bin interval the mean value found is 17.36 GeV and the error bar we find is 1.4 GeV, which seems quite reasonable ¹. If, like Gordon [22], we push the fragmentation functions to their limit and evaluate each quark's contribution at the lowest fragmentation scale allowed by the parameterizations of [21] ($\sqrt{2}$ GeV for the light flavours, the quark's mass for the two heavy ones), we find, as he did, an increase in the cross section. The agreement with the data at high- p_T is then found to be perfect. This may seem an *outré* choice of fragmentation scale but it must be said it is as justified, in principle, as taking $M_F = p_T$ ². This choice of scale, in fact, allows us to reproduce the data for p_T as low as ~ 3 GeV without the need for any resolved contributions.

We next consider the K_S^0 results from [8] - these are perfectly reproduced by the SM predictions (see figure 3.b from ref. [8]) but we remark they do not extend to large values of p_T . It would be interesting to check if, for large p_T , one finds a discrepancy like that seen in the π^0 cross section. For such low values of p_T we cannot expect to fully reproduce the K_S^0 data but we must confirm if the ICQ hypothesis does not ruin a possible agreement with experiment (in other words, we need to verify that the ICQ predictions are not larger than the data). As we see in fig. (5), again the low- p_T points are not reproduced by the ICQ curve but interestingly, the experimental point immediately above the charm threshold is - this agrees nicely with our hypothesis in the previous section, in which we considered that charm production was a process already dominated by perturbative contributions. Recent results for inclusive charged hadron production in two-photon collisions [9] have also revealed large discrepancies between the SM predictions and the experimental results. For charged kaons our results are shown in fig. (6). Again, we see that the ICQ calculation with the standard choice $M_F = p_T$ improves the agreement with the experimental results; the same choice of lowest possible fragmentation scale gives very good agreement for all values of p_T larger than about 2 GeV, except for the final point ³. The deviation there is small and would surely be overcome if NLO contributions were taken into account. More problematic are the charged pion results, as this is the channel for which the deviation between SM prediction and experimental result is largest - a factor of almost 40, judging from fig. (7). We see from fig. (8) that with the “normal” choice of fragmentation scale the ICQ theory only fits the data until $p_T \simeq 6$ GeV. Pushing the fragmentation functions to their limit we get agreement up to about 12 GeV, but a large discrepancy remains for the experimental point with the highest value of p_T , a factor of about 3. One could say that it is

¹I thank Pablo Achard for clarifying this issue for me.

²Lest the reader thinks we are dishonestly favouring ICQ theories let them be assured that even considering the p_T error bars and the same extreme choice of fragmentation scale the discrepancy between the data and the SM predictions remains immense.

³The error bars shown in fig. (6) were calculated in the same manner as those of fig. (4).

impressive enough that with a tree-level calculation alone we passed from a factor of 40 to a factor of 3, but the disagreement with the data remains.

A general comment about these results: they are strongly dependent on the fragmentation functions, as we showed by varying the fragmentation scale. The improvement over the FCQ predictions, regardless of that dependence, is unequivocal, but good agreement with experimental results is achieved in three cases only with a peculiar (if allowed) choice of scale. The disagreement we found for the case of charged pions might have to do with a feature observed by the L3 collaboration - they compared, in ref. [9], the π^\pm data obtained with the π^0 results from [8]; it was expected that the ratio between both sets of data points should be around 4, a factor of 2 due to doubled η coverage for charged pions - an assumption verified by the data, see figure (3) of [9] - and a factor of 2 from the assumption in the fragmentation functions of [21] that $D_q^{\pi^0}(z, M_F^2) = D_q^{\pi^\pm}(z, M_F^2)/2$. Now, this latter assumption is well motivated by various sets of experimental data (see [21] and references therein) but the fact remains that (see figure (2.b) of [9]) for $p_T \geq 4$ GeV the ratio between π^\pm and π^0 data seems to be centered around 6, not the expected value of 4. So perhaps the data is showing us that the assumption relating the fragmentation functions of neutral and charged pions is incorrect in this domain of p_T and s . The question remains open. Another important remark: these are LO results. The NLO fragmentation functions are not largely different from the LO ones, but clearly a NLO calculation in specific ICQ models is necessary. Finally, agreement with the high- p_T data is found but the question remains as to whether one hasn't destroyed the agreement found for small values of transverse momentum within the SM, where non-perturbative calculations dominate. The obvious comment to make is that the resolved contributions considered in refs. [8, 9] were calculated in the context of the SM; to verify whether an ICQ model agrees with the data for low p_T it would be necessary to repeat those calculations within the framework of the particular model under study.

3 Evidence for fractional quark charges

The SM is an extraordinarily successful theory, a fact reinforced by precision measurements agreeing with two and three loop calculations made in the framework of the Glashow-Weinberg-Salam theory. And yet, as we shall shortly see, direct experimental evidence for fractional electric quark charges is very limited. This is not surprising: due to confinement we have no direct access to quarks and must study the results of their hadronisation, a task complicated by non-perturbativity at low energies. An overview of the experimental evidence for the nature of quarks' charges was done elsewhere [23], we analyse in detail some of the evidence for FCQ usually quoted in the literature and try to argue that ICQ models are not excluded by it. Before we start we point out that in what concerns purely leptonic processes both models are obviously identical.

• **Single photon processes:** as was mentioned in section 1 the R quantity is usually presented as evidence for FCQ; and yet we showed it is predicted identically for both FCQ and ICQ theories. This is an example of an interesting (one might also say perverse) feature of ICQ theories - for any process involving a single photon they mimic FCQ models (at tree level at least). This can be shown in a general manner if we recall that in ICQ theories, due to different gauge symmetry breaking, the electromagnetic current J_μ^I is the sum of two pieces: $J_\mu^I = J_\mu^F + J_\mu^8$ where J_μ^F is the usual FCQ current, corresponding to the electric charge operator $Q_F = T_3 + Y/2$. J_μ^8 is the extra ICQ contribution, non-zero only for particles with colour - the charge operator associated with it is $Q_8 = \lambda_8/\sqrt{3} = \frac{1}{3}\text{diag}(1, 1, -2)$, where λ_8 is the eighth Gell-Mann matrix. It is trivial to see that in an ICQ theory the electric charge of a

quark becomes colour dependent, for an up-type quark it is $q_u = (+1, +1, 0)$ and for a down-type one, $q_d = (0, 0, -1)$. The fundamental thing to retain from this is the fact the ICQ current is the sum of the FCQ one with a term that is traceless in colour space. Now, we know colour is not observed in nature, only $SU(3)$ singlets. If the initial and final states of any given process are colour singlets then the basic tenets of quantum theory tell us that we must sum the amplitude on the colour indices and divide its square by the total number of colours (as if we were dealing with an interference experiment). The sum on the colours will correspond to taking the amplitude's trace in colour space. Thus, for any process involving a single photon (a single current, then), the extra ICQ contribution is cancelled and the result is the same of an FCQ theory. The current J_μ^I being the result of gauge symmetry breaking, this result holds for any order of perturbation theory as ICQ theories are renormalisable.

ICQ and FCQ theories are therefore indistinguishable for single photon processes (also single Z^0 processes - see ref. [18], for instance). This would in principle include deep inelastic scattering experiments (two-photon interactions in these are an extremely small correction to the main interaction) although in studying these one will have to take into account the different spectrum of gluons of ICQ models. ICQ theories also predict identical rates for (most) meson radiative decays. There is a wealth of data on radiative decays of heavy mesons (for reviews, see for instance [24, 25]), but these involve dipolar transitions between different states of the quark bound states, with the emission of a single photon. And because a single photon is involved both ICQ and FCQ theories would have the same predictions for those processes. Of course, cascade decays with the emission of several photons are a succession of single photon decays and as such are identical in both models.

The only way to obtain a difference between ICQ and FCQ models in photonic processes is to consider a situation where at least two J^I currents are involved; this will lead to a transition amplitude between two states $|i\rangle$ and $|f\rangle$ of the form $\langle i | \dots J_\mu^I J_\nu^I \dots | f \rangle$. The end result must still be a colour average but this time there will be a $(J^8)^2$ term which is not cancelled and produces a substantial difference between ICQ and FCQ, as was apparent in the values of $R_{\gamma\gamma}$ found earlier.

• **Jet charges:** Feynman and others [26] proposed a clever way of measuring the quarks' electric charges using neutrino-nucleon inelastic scattering. In a $\nu - p$ collision, if the final state includes a positron then an interaction with the exchange of a W^+ boson surely occurred and inside the proton only d or s quarks could interact with the W^+ . Thus the jets produced in this reaction will almost certainly result from the hadronisation of an up-type quark and a measurement of their average charges should yield information about the quark's own. The experiments were performed [27] and the results agree with fractional quark charges. How do ICQ theories fit in this picture? An ICQ theory such as the one proposed in [18] has W bosons identical to the SM's so the partonic interactions would not be different. But once again ICQ and FCQ predictions are found to be the same and the explanation is essentially the same used in single-photon processes: because no individual colours are observed the result of any attempt to measure a quark's charge in this manner will be the colour average of the electric charge; for an up-type quark the result of a jet-charge measurement should then be

$$Q_{up}^{jet} = \frac{1}{3} \sum_{i=1}^3 q_{up}^i = \frac{1}{3} (1 + 1 + 0) = \frac{2}{3} \quad , \quad (7)$$

and likewise for a down-type quark, with the result $-1/3$. So, though ingenious, jet-charge measurements do not allow us to distinguish between ICQ and FCQ models.

• **Meson radiative decays:** we already discussed dipolar transitions in heavy mesons and argued they are predicted identically in both ICQ and FCQ models. There are however many experimental results of two-photon meson decays and these could in principle distinguish between both models. An important case is the decay of η mesons into two photons, which have been used in the past as evidence against ICQ theories [28]. This is based on the fact that a simple PCAC analysis of such decays yields for its width the expression [29]

$$\Gamma_{\gamma\gamma}^X = \left(\sum_{\text{colour}} \langle e_q^2 \rangle \right)^2 \frac{\alpha^2}{32\pi^3} \frac{m_X^3}{f_X^2} \quad , \quad (8)$$

where α is the fine structure constant, m_X and f_X are the mass and decay constant of the meson under consideration and $\langle e_q^2 \rangle$ the mean value of the squared charges of the quarks in the state given by the meson's wave function. At this point, in a simple approach, one considers the so-called “nonet symmetry”, that is, the equality of the decay constants for the mesons belonging to the same flavour multiplet. The emblematic cases for comparison between ICQ and FCQ theories are the pion, the η_1 and the η_8 states, so we assume $f_1 = f_8 = f_\pi$. It is simple to show that for the pion and η_8 states the widths are the same for both cases but, for the η_1 , the ICQ width is 4 times larger than the FCQ one. The first obvious retort to this “evidence” against ICQ theories is that it relies heavily on untested theoretical assumptions, to wit the equality of the decay constants. There is in fact no *a priori* reason why nonet symmetry should hold - in a naïve quark model such an assumption might be plausible if the physical mesons η and η' (which result from the mixing of the η_1 and η_8 states) were ideally mixed but as argued in ref. [28] that is hardly the case. Further, more elaborate calculations have found serious deviations from nonet symmetry - for instance, using a Hidden Local Symmetry model, the authors of ref. [30] have found $f_1 = 1.4 f_8$. Chanowitz [28] deduced equations for a ξ parameter ($\xi = 1$ for FCQ, $\xi = 2$ for ICQ) in terms of experimentally measured quantities which were in principle independent of the nonet symmetry hypothesis and seemed to favour FCQ over ICQ. The problem there is that from the start those equations were less reliable if the theory being tested was ICQ. And it was shown later that even for the “normal” FCQ theory Chanowitz's equations could not be applied in a naïve manner as they didn't take into account the existence of a more complex mixing between η_1 and η_8 [31]. Pseudoscalar meson decays are an exceedingly difficult field of study, where great doubts still persist. For instance, different groups claim evidence for the presence of a significant gluon component in the η and η' states [32] or against it [31].

Heavier quarkonia two-photon decays have also been studied in detail but one finds a situation similar to the lighter mesons - there is a remarkable FCQ prediction [24],

$$\frac{\Gamma(\eta_c \rightarrow \gamma\gamma)}{\Gamma(J/\Psi \rightarrow e^+ e^-)} = 3 Q_c^2 \frac{|\eta_c(0)|^2}{|J/\Psi(0)|^2} \quad . \quad (9)$$

If one *assumes* the equality of the meson's wave functions at the origin (the same type of hypothesis that nonet symmetry is based on) the FCQ prediction is a factor of 4/3, whereas the ICQ result would be 3. The current experimental values favour the FCQ result. However, to obtain this “prediction” we needed to make an extra assumption regarding the (unknown) wave functions of quark bound states, and such an assumption might be an oversimplification: it has been shown [40] that the $J/\Psi \rightarrow \gamma \eta_c$ magnetic transition is substantially underestimated if one assumes both particles' wave functions are identical. Theoretical calculations of the η_c two-photon amplitude also vary considerably (from 5 to 10 KeV [40], the experimental value being 7.2 ± 1.2 KeV, depending on whether one uses QCD sum rules [41] or a Bethe-Salpeter formalism [42]. In fact, the authors of ref. [42] find considerable differences between both mesons'

wave functions. With the charm quark mass dependence taken into account in corrections to eq. (9), we find that if the η_c and J/Ψ wave functions differ by about only 20%, the current experimental results would actually favour ICQ theories. Like in the lighter mesons, then, the theoretical description of the mesons' structure is much more complex than simple formulae like (9) lead to believe. With this in mind we must ask ourselves, are we testing the character of the quarks's electric charges or our models about their bound states? We argue that this uncertainty leaves room for speculation on ICQ models.

• **Final state radiation in hadronic interactions:** Brodsky and collaborators [33] suggested an interesting method for establishing the character of the quarks' charges, by measuring the asymmetry between deep inelastic scattering of the proton using electrons or positrons. The difference between the cross sections for the processes $e^- p \rightarrow e^- \gamma X$ and $e^+ p \rightarrow e^+ \gamma X$ would select the Bethe-Heitler-Compton interference term, proportional to the cube of the partons' electric charges at tree-level. This would in principle, then, provide us with a clear measurement of the values of the quarks' charges. The initial experiments [34] were inconclusive, with results that could even be seen favouring the ICQ models. Further experiments were conducted, adapting this idea to final state radiation measured in $e^+ e^- \rightarrow 2 \text{ jets}$ [35], and still, the results were inconclusive. A detailed theoretical analysis of these results was given in refs. [36], where it was shown that the proposed measurements were actually not very sensitive to the model considered.

The best argument against ICQ theories is an indirect one: the fact they (usually) predict gluons having mass and electric charge. The authors of refs. [13, 37], for instance, choose a gauge symmetry breaking mechanism that gives mass to all gluons all the while preserving a global $SU(3)$ symmetry. Others have given mass to gluons by means of a four-vertex ghost field [38]. Cornwall proposed a mechanism for dynamic generation of gluon masses within a theory with unbroken colour gauge symmetry [39]. According to the Particle Data Group [43] the current limit on the mass of the gluon is “a few MeV”. That, however, is a theoretical bound, derived from arguments that assume all gluons are degenerate in mass [44]. Also, as others have discussed [17], the arguments of [44] neglect to take into account the quantum field theoretical aspects of the gluon-quark interactions, which casts doubt over their final conclusions. The best experimental evidence for the existence of eight massless gluons is the precision measurements agreeing with two and three loop QCD calculations, from which it is established that the running of the strong coupling constant is in agreement with an $SU(3)$ β -function [43], on an energy range from ~ 2 to 200 GeV. This remarkable result has to be taken into consideration when considering ICQ theories, whatever model we consider has to reproduce the low-energy behaviour of α_S . A trivial remark is that these experimental results do not, in principle, contradict the existence of light massive gluons, with masses of the order of 1 GeV (possibly even larger, considering the experimental uncertainty in the values of α_S at low energies). This because the coefficients of the α_S β -function at a given energy scale M depend on the number of particles (both fermions and gluons) with masses smaller than $M/2$ - a crude explanation for this well-known fact is to say that those are the particles “circling” in the loops that contribute to the renormalisation of the gluonic propagator. Particles with larger mass have been “integrated out” of the theory (a simple example of this is the change in the coefficient of β_{α_S} once the bottom quark threshold is crossed). It seems reasonable, then, that the α_S low-energy evolution does not preclude ICQ models such as those considered in refs. [16, 17], with gluon masses smaller than ~ 1 GeV. In fact, in ref. [17], Field gives additional experimental arguments for the existence of massive gluons by showing that the decays of the J/Ψ and Υ mesons are better explained assuming a gluonic mass of about 1 GeV. Furthermore, we must remark that it is not a necessary implication that ICQ models have no massless gluons - in ref. [18] a model is constructed in which three

gluons remains massless and neutral and five others gain mass, four of which are charged. This example shows that quarks having integer charge is not necessarily tantamount to gluons having mass and charge. Again, we would argue that these considerations - though hardly conclusive - leave us enough room to speculate on the possibility of ICQ models.

4 Concluding remarks

Any conclusions on this matter must necessarily be modest. The Standard Model, and QCD in particular, are established theories responsible for a wealth of extremely precise predictions, well confirmed by numerous experiments. The results from LEP2, however, are undeniable: at high energies, when our perturbative models should work best, they fail to reproduce the experimental results in four separate measurements. That these huge discrepancies occur in the two-photon channel is also very important - this is a direct probe into the electric charges of quarks and the exact place where one would expect sizeable differences between ICQ and FCQ models. They are a clear indication that something is wrong in our understanding of particle physics at very high energies, and we studied a particular solution for this problem. We have performed tree-level calculations using integer charged quarks and showed that such models perfectly reproduce the open production of heavy quarks in photon-photon collisions at LEP2. An estimation of higher order contributions to these cross sections was also made and indicates the agreement should remain if loop calculations are performed. ICQ theories also improve considerably the agreement between theory and experiments on the inclusive production of pions and charged kaons via the two-photon channel at LEP2. Perhaps we could discount these results as a numeric coincidence if we had found agreement with the data in a single observable, but in this paper we studied four different channels. Very good agreement with the data is even obtained for π^0 's and K^\pm 's by choosing the lowest fragmentation scale possible. We must remember that ICQ models improve the agreement with data for high p_T values but we do not know what will happen in the low energy region once non-perturbative contributions are taken into account. We have reviewed the evidence for fractional quark charges and argued that it was not conclusive - the best arguments stem from two-photon meson decays but their analysis only points to FCQ under the assumption of stringent theoretical assumptions. Nonet symmetry has proven to be false and, for heavy mesons, the equality of wave functions is not supported by relativistic calculations. The issue of gluon masses is a fundamental one, but there are ICQ theories that have massless gluons, and others for which the gluonic masses are so small as to not challenge, for instance, the low energy evolution of the strong coupling constant. Evidence for gluons being massless is also indirect, whereas the two-photon results provide direct evidence on the quark charges. It is also worth mentioning that though ICQ models help explain the two-photon discrepancies found at LEP2, they will not, in principle, have an impact on the excess of open bottom quark production observed at HERA [45, 1]. Regardless of whether one believes in ICQ models or not, it seems clear they do a better job than the SM at describing the two-photon data. As such they are, to the best of our knowledge, at present the only explanation for the discrepancies observed at LEP2. We argue that these results are interesting enough to take the ICQ hypothesis seriously. At this point more refined calculations, involving higher order contributions and those coming from resolved processes, are necessary. It would also be desirable to obtain data from LEP collaborations other than L3 - despite their excellent work in studying these channels, independent confirmation of large discrepancies with the SM would clearly be reassuring.

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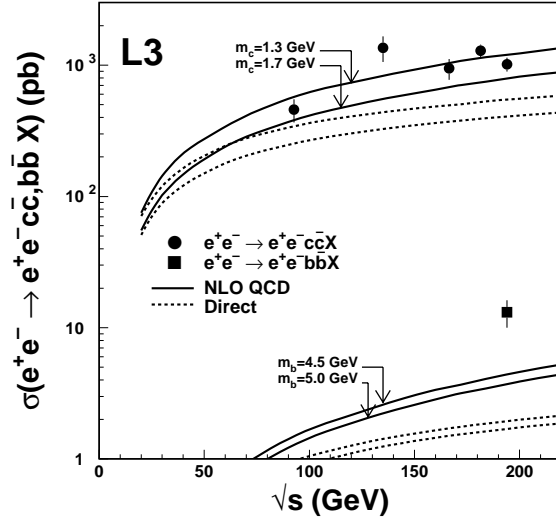


Figure 1: Cross section for production of $c\bar{c}$ and $b\bar{b}$ pairs at LEP through the two photon channel from the L3 collaboration [7].

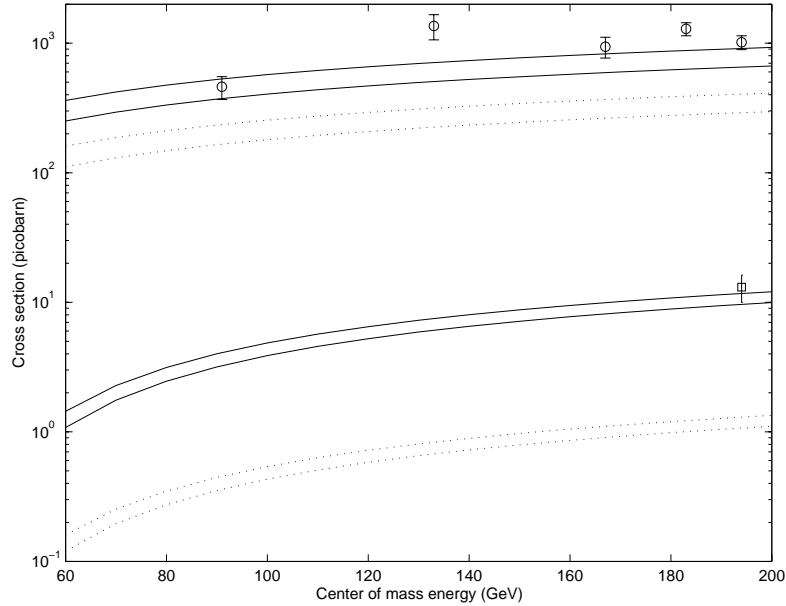


Figure 2: Tree-level cross sections for production of charm and bottom quarks via the two-photon channel for FCQ (dotted lines) and ICQ (solid lines) models. The sets of two lines correspond to quark masses varying in the intervals $1.3 \leq m_c \leq 1.7$ GeV, $4.5 \leq m_b \leq 5.0$ GeV.

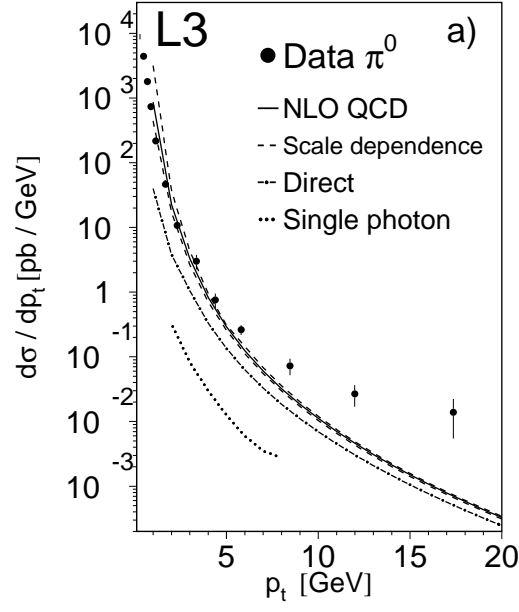


Figure 3: Inclusive differential cross section for π^0 production in photon-photon collisions at LEP2, for $|\eta| < 0.5$ and $s > 5$ GeV. The data is compared to a NLO QCD calculation, with the direct contribution represented by the dot-dashed line. L3 collaboration [8].

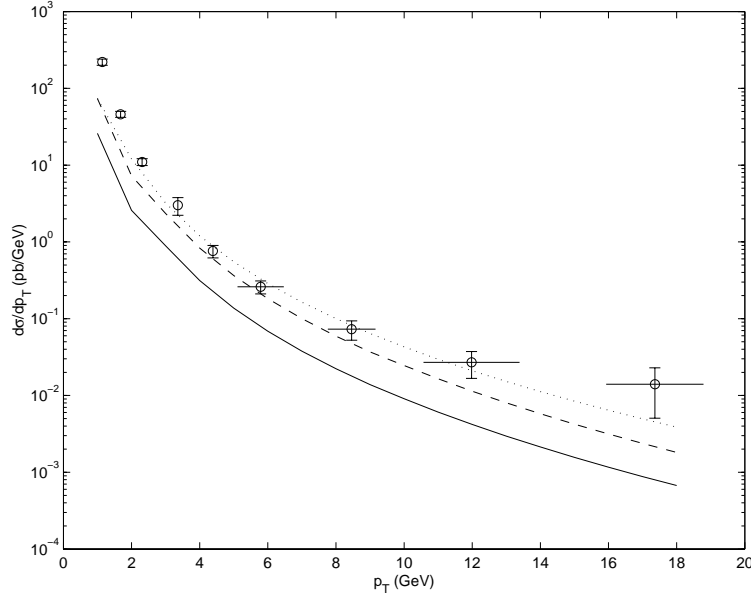


Figure 4: Inclusive differential cross section for π^0 production in photon-photon collisions at LEP2, for $|\eta| < 0.5$ and $s > 5$ GeV - the data is compared to a tree-level SM calculation (solid line) and ICQ calculations with $M_F = p_T$ (dashed line) and the lowest value of M_F possible, described in the text (dotted line).

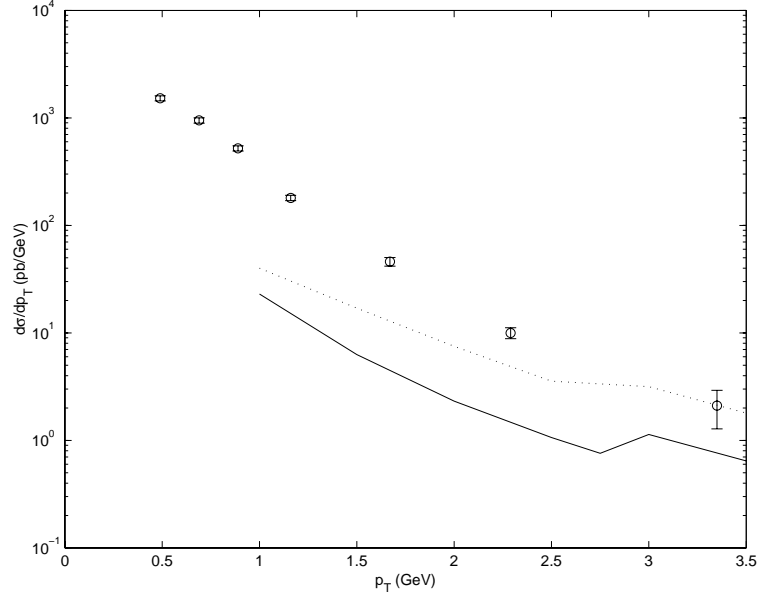


Figure 5: Inclusive differential cross section for K_S^0 production in photon-photon collisions at LEP2, for $|\eta| < 1.5$ and $s > 5$ GeV - the data is compared to a tree-level SM calculation (solid line) and ICQ calculation with $M_F = p_T$ (dotted line). The structure at $p_T \simeq 3$ GeV is due to the charm production threshold in the fragmentation functions [21].

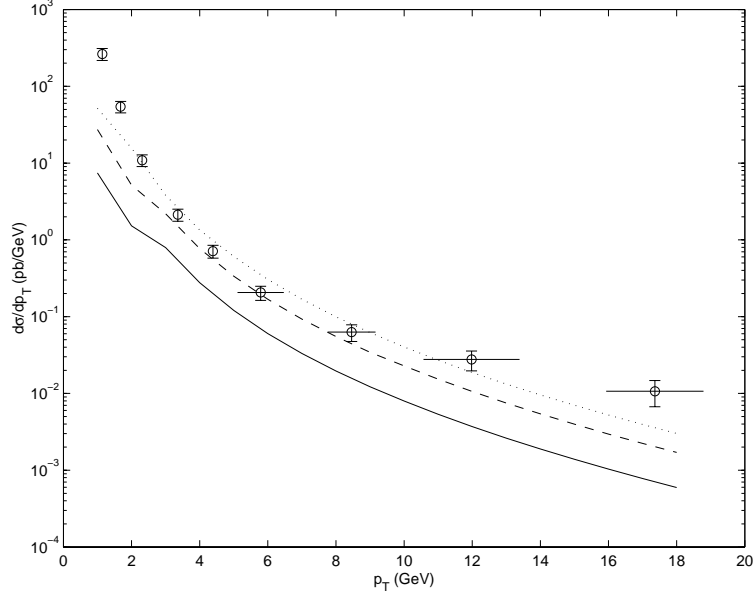


Figure 6: Inclusive differential cross section for K^\pm production in photon-photon collisions at LEP2, for $|\eta| < 1$ and $s > 5$ GeV - the data is compared to a tree-level SM calculation (solid line) and ICQ calculations with $M_F = p_T$ (dashed line) and the lowest value of M_F possible, described in the text (dotted line).

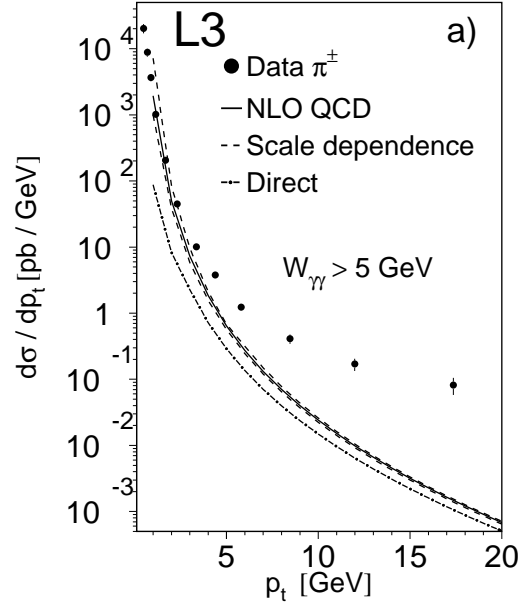


Figure 7: Inclusive differential cross section for π^\pm production in photon-photon collisions at LEP2, for $|\eta| < 1$. The data are compared to a NLO QCD calculation, with the direct contribution represented by the dot-dashed line. L3 collaboration [9].

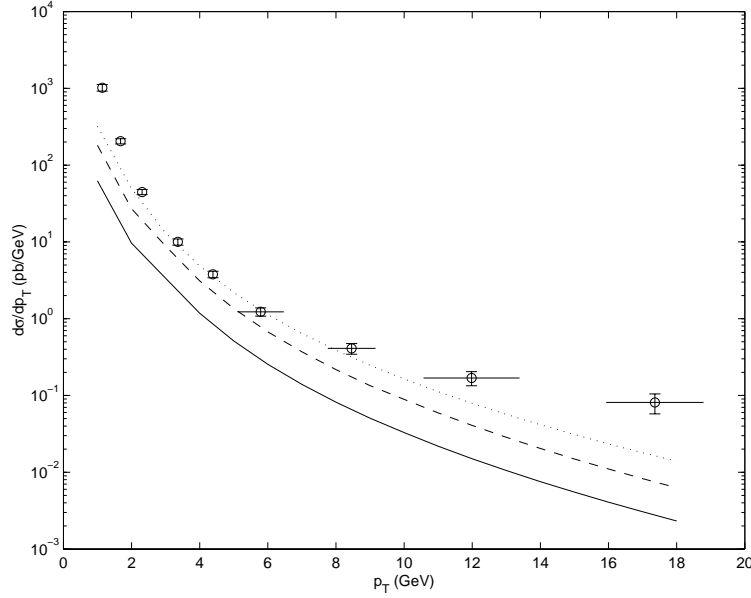


Figure 8: Inclusive differential cross section for π^\pm production in photon-photon collisions at LEP2, for $|\eta| < 1$ and $s > 5$ GeV - the data is compared to a tree-level SM calculation (solid line) and ICQ calculations with $M_F = p_T$ (dashed line) and the lowest value of M_F possible, described in the text (dotted line).